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Targeted control measures for ecological restoration in Western Fujian, China

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ABSTRACT

Ecosystem degradation is caused by interactions among multiple factors, including climate change and human activity. Therefore, we must understand the key factors that underlie ecological degradation and determine their impacts on ecosystem change before we can undertake ecological restoration. To test this hypothesis, we proposed a measure that we call "targeted measures to control ecological restoration". This approach calculates the contribution of every key factor and control measure to ecosystem change during ecological restoration; by identifying the key factors, it helps managers to design an effective restoration strategy based on those factors. To test this approach, we performed a case study from 2000 to 2016 in four towns of Changting County, Fujian Province, China. Although the vegetation cover decreased by 3.1% from 1984 to 1999, vegetation cover and vegetation species richness increased by 94.8 and 616.7%, respectively, in the test areas where new measures were implemented from 2000 to 2016. These rates were 4.5 and 148.2 times those in the control area, respectively. Our new approach focuses on repairing degraded ecosystems rather than creating new ones. The case study suggests that understanding ecosystem dynamics can help us deal more effectively with the simultaneous effects of climate change and human activity.

1. Introduction

Ecosystem degradation is causing major environmental issues around the world, including soil erosion and desertification (Sivakumar, 2007; D'Odorico et al., 2013). This degradation affects 36×10^6 km^2 globally, accounting for 25% of the world's land area and causing direct losses of up to 850×10^9 USD annually (D'Odorico et al., 2013). Ecosystem degradation is particularly serious in China, where 3.3×10^6 km^2 of degraded land accounts for one third of the total national land area; this affects more than 400 counties in 18 provinces, threatens the livelihoods of 400×10^6 people, and keeps 12×10^6 people in poverty, amounting to 28.5% of China's impoverished population (Wang et al., 2008). With ecosystem degradation becoming more serious and the area of arable land decreasing, poverty is also worsening (Olukoye and Kinyamario, 2009). Due to a lack of choices, residents in degraded areas are forced to engage in unsustainable activities such as deforestation, overgrazing, and land reclamation for agriculture, thereby exacerbating environmental degradation (Sietz et al., 2011). Because poverty leads to ecosystem degradation, and ecosystem degradation worsens poverty, this vicious circle is called the "poverty trap" (Cao et al., 2009; Kates and Dasgupta, 2007). It prevents sustainable socioeconomic development and threatens the long-term livelihoods of residents of affected areas (Tallis et al., 2008).

Ecosystem degradation results from interactions among multiple natural and human factors (Cao et al., 2014; Feng et al., 2015). Climate change and human activities both strongly affect vegetation change, and changes in vegetation communities in turn affect climate change (Shi et al., 2007; Ma et al., 2013) and human activities (Sun et al., 2012; Ma et al., 2014). Some natural sciences researchers suggest that climate change can degrade soil quality, vegetation cover, the species composition, and hydrological cycles, thereby resulting in ecosystem degradation (Marland et al., 2003; Zhou et al., 2009). At the same time, humanities researchers suggest that unsustainable human activities such as overgrazing, over-harvesting, and excessive groundwater exploitation create tremendous pressure on ecosystems, leading to degradation that accelerates soil erosion and other forms of ecosystem degradation (Zhao et al., 2005; Zheng et al., 2006). However, previous studies focused either on meteorological factors related to climate change (e.g., Sivakumar, 2007) or on anthropogenic factors related to human activities (e.g., Olukoye and Kinyamario, 2009). Few studies

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quantified the simultaneous effects of interactions among multiple factors, including both natural and human factors, based on long-term monitoring (Marland et al., 2003; Zhou et al., 2009). Because the approaches and data from the natural sciences and the humanities have not been combined, the research results provide a weak basis for environmental management, making it difficult to improve environmental protection.

Once an ecosystem has become sufficiently degraded that it requires ecological restoration, conditions are not conducive to the survival of most species. To solve this problem, traditional ecological restoration has focused on creating new ecosystems (e.g., when afforestation is chosen as the restoration option to create a forest that replaces the site's original grassland) with conditions that promote survival of the new species. Now, ecologists are increasingly recognizing the potential of rebuilding degraded ecosystems by taking advantage of natural mechanisms (e.g., biotic interference). However, the interactions between biotic factors and climate alter the results of environmental engineering by altering the underlying mechanisms responsible for ecosystem change (Suding et al., 2004; Lv et al., 2016). Because human activities can promote degradation, it's essential to understand the relationships between restoration mechanisms and socioeconomic development, thereby allowing more effective responses.

If we understand how natural and anthropogenic factors interact to produce a degraded ecosystem, we can manage those factors in ways that will help that ecosystem recover, thereby eliminating the need to create a completely new ecosystem. To do so, we must first identify the key factors responsible for degradation and recovery, and quantify their impacts on ecosystem change. Because unsustainable human activities are a primary cause of degradation, it's essential to identify their impacts so as to avoid activities that promote degradation processes and to encourage activities that promote recovery processes. The ecological restoration can only succeed when it simultaneously accounts for the ecological environment (e.g., climate, topography) and the production and living behaviors of residents of degraded areas. For example, it may be possible to develop green industries that both promote ecological restoration and improve livelihoods (Cao et al., 2017). This permits a win–win solution that combines ecological restoration with improved livelihoods. This approach should avoid the disadvantages of traditional projects, in which reclamation efforts targeted at impoverished people paradoxically make them poorer (Cao et al., 2017).

Unfortunately, ecological restoration in China and around the world still largely relies on a traditional approach that only focuses on ecological factors and ignores socioeconomic factors (Meli et al., 2017; Newmark et al., 2017). To improve the effectiveness of ecological restoration, it's necessary to move towards a newer, more holistic approach. In the present study, we hypothesized that taking advantage of natural restoration mechanisms while accounting for the factors that cause degradation could improve the effectiveness of restoration. We call this approach "targeted measures to control ecological restoration", and tested this method in a 16-year case study in China's Fujian Province. With targeted measures to control ecological restoration, researchers or project managers calculate the contribution of every key factor and every control measure to the mechanisms that underlie ecosystem change. Addressing each of these factors lets degraded ecosystems gradually recover to a healthy, stable state. This approach works by accounting for the coupling mechanisms among socioeconomic development, policy development, and ecological restoration (Meli et al., 2017).

2. Targeted measures and methods

2.1. Study area

Changting County is located in the western part of China's Fujian Province (between 116°00′45″E and 116°39′20″E and between 25°18′40′N and 26°02′05″N), and covers an area of 3.1×10^3 km². Annual precipitation averages 1730.4 mm. The annual temperature averages 18.3 °C (with an average minimum of 7.9 °C). In 2016, the county's population was 514.4×10^3 and its per capita income was 11 442 RMB (Cao et al., 2009).

Changting County historically had high vegetation cover. However, since the middle of the 20th century, government policy promoted forest harvesting and planting of monoculture forests. Paradoxically, this led to decreased vegetation cover, decreased biodiversity, severe soil erosion, frequent flood disasters, damage to the forest landscape, and other problems. There are many regions around the world similar to Changting County in terms of its severity of ecological degradation and its socioeconomic conditions, although the climate and geography may differ. The Brazilian rainforest region is one example (Escobal and Aldana, 2003). This part of Brazil had abundant ecological resources in the past, but Brazilians overexploited forest resources to encourage socioeconomic development, thereby causing severe ecosystem degradation in many areas. As a result, even though residents received short-term income from their activities, they remain impoverished because the ecosystems no longer support wood harvesting or other economic activities that could replace that harvest.

To prevent further land degradation, Changting County's government reformed property rights in the 1980s to make residents responsible for management of the forest. Under these reforms, 90% of the forest was distributed to farmers. Wood harvesting was required to follow the national wood harvesting policy, under which harvesting required the permission of the local forest administration. However, in contrast with expectations, poor residents of the county failed to consult the forest administration or learn how to protect their forest; instead, they sold the trees as fuel wood without permission and without any knowledge of sustainable harvesting techniques, leading to a rapid loss of forest cover and further aggravation of soil erosion and ecological degradation. The county's total area of soil erosion decreased from 974.6 km² in 1984 to 737.6 km² in 1999, but the area of severe soil erosion (> 8000 t km^{-2} yr^{-1}) doubled, from 55.8 km² to 113.2 km² (Table 1). The vegetation cover and forest cover both decreased by 3.1% and the number of vegetation species decreased by 11.1% during this period (Table 1). At the same time, despite the decreasing total area of soil erosion, ecosystem degradation remained serious in some areas (Zeng and Zhong, 2002; Cao et al., 2009).

2.2. New measures

Despite the serious soil erosion, this area was not included in China's national Grain for Green and natural forest protection projects. In 2000, Changting County's Soil and Water Conservation Bureau summarized its historical experiences and lessons, with the goal of implementing ecologically harmonious development of the county's economy and society rather than focused only on the environment. At that time, we provided advice on how to restore the natural ecosystems

Table 1
Changes in vegetation characteristics and soil erosion in Changting County from 1984 to 1999, before implementation of the new approach.

	1984	1999	Change (%)
Vegetation cover (%)	64	62	–3.13
Forest cover (%)	65	63	–3.08
Soil erosion area (km²)	974.60	737.59	–24.32
Light soil erosion (< 2500 t km^{-2} yr^{-1})	594.73	478.65	–19.52
Moderate soil erosion (2500 to 5000 t km^{-2} yr^{-1})	207.13	58.93	–71.55
Heavy soil erosion (5000 to 8000 t km^{-2} yr^{-1})	117.13	86.85	–25.85
Severe soil erosion (> 8000 t km^{-2} yr^{-1})	55.80	113.16	102.80
Vegetation species			
Family (no.)	42	39	–7.14
Genus (no.)	64	57	–10.94
Species (no.)	81	72	–11.11

Table 2
The contribution of each statistically significant factor to the changes in the vegetation cover, area of soil erosion, and number of vegetation species from 1985 to 1999 in Changting County.

	Vegetation cover		Soil erosion area		Vegetation species	
	r	Contribution (%)	*r*	Contribution (%)	*r*	Contribution (%)
Rural population	−0.991**	23.88	0.976**	14.79	0.953**	13.10
Rural net income	0.919**	9.78	−0.841**	0.73	0.925**	12.25
Area of fruit tree orchards	−0.938**	16.02	−0.927*	12.84	−0.910**	12.96
Area in which forest harvesting is forbidden	0.663**	6.29	−0.112**	4.71	−0.059**	6.37
Methane-generation facilities	−0.291**	12.59	−0.535**	3.18	0.680*	6.85
Length of roads and railways and areas of mining land that underwent revegetation	0.938*	9.61	−0.967	36.71	0.932	12.61
Farmland area	−0.249**	3.11	−0.210*	4.48	−0.286**	6.18
Afforestation area	0.101*	9.55	−0.117	5.10	0.110*	11.59
Mean annual temperature	0.016	8.47	0.003	17.42	0.030	5.48
Precipitation	0.312**	0.70	0.353**	0.04	−0.279**	12.62

Notes: Significance levels: ** 1%, * 5%.

of the study area. The results were impressive (Cao et al., 2009; Cao et al., 2017). However, based on the results in subsequent years, we began to realize that our advice had worked so well because it focused on the key factors underlying ecosystem change, even though we had not explicitly quantified those factors. Thus, in the present study, we reviewed the data from our previous research and subsequent years to calculate the contributions of every key factor to the change in vegetation cover Changting County since 1984 (Table 2; see Section 2.4 for details). The rural population decrease that has accompanied China's rapid urbanization accounted for 23.9, 14.8, and 13.1% of the increase in vegetation cover, decrease in soil erosion area, and increase in the number of vegetation species, respectively. The creation of economic forest through the establishment of fruit tree plantations (12.8 to 16.0% of the total change in these parameters), methane-generation facilities (3.2 to 12.6%), and revegetation of roadside slopes (9.6 to 36.7%) also played important roles.

Based on these calculations, we selected four towns (Cewu, Hetian, Sanzhou, and Zhuotian) to test whether our hypothesis about targeted measures to control ecological restoration could explain the results. Based on the results in Table 2, we tested whether the following restoration measures could explain the results:

1 Developing economic forest through the establishment of fruit tree plantations, aquaculture, and pig breeding (primarily pigs) to increase resident incomes;
2 Using livestock excrement as an input for methane-generation facilities to meet rural energy needs;
3 Forbidding large-scale cutting of natural forest to allow natural recovery of the forests;
4 Urbanization and ecological migration to relieve the stress on the rural environment;
5 Intensifying soil and water conservation efforts on roadside slopes and in mining areas to protect the environment.

To provide a comparison (the "control"), the other 14 towns in the county continued to follow the traditional soil and water policies.

2.3. Study design and observations

In our that previous study (Cao et al., 2017), we only examined the results of a new approach to ecological restoration. In the present study, we extended the data collection period to 2016, then reanalyzed the data to identify the key factors responsible for those previous results. The goal of this reanalysis was to move from description of the results to identification of the driving factors responsible for those results.

To monitor the effect of the targeted measures to control ecological restoration, we randomly selected four towns (Nansha, Gucheng, Xinqiao, Sidu) from the 14 control towns outside the new project area to provide a comparison with the four selected towns. We randomly selected five villages from every town, and obtained data on the forest cover (the area of forest and the forest cover within this area), number of vegetation species, area of soil erosion in each of the four severity categories shown in Table 1, and other ecological and economic indicators to access the effects of the new approach.

In summary, we established vegetation monitoring plots in each village, and used them to measure the changes in the vegetation cover of trees and other vegetation. These measurements were performed towards the middle and end of the growing season from 2000 to 2016. We also established runoff-collection ponds below each plot to monitor the amounts of soil erosion during the same period. For details of the design and these measurements, see the literature of Cao et al. (2017).

2.4. Analytical methods

To fully understand which factors affect ecosystem degradation and recovery, it's first necessary to choose a metric that can describe the state of ecosystem health. Based on the successful approach in our previous research (Feng et al., 2015), we chose the normalized-difference vegetation index (NDVI), as this index provides a good proxy for vegetation cover and facilitates monitoring of long-term changes in vegetation cover over large areas. The NDVI dataset used in this paper came from the AVHRR GIMMS group (http://glcf.umd.edu/data/ndvi/). Because of high cloud cover during the growing season at our study sites, only a part of the NDVI images were usable. In addition, the spatial resolution was very coarse compared to the size of our study sites. Thus, in future research, it will be necessary to obtain images with higher spatial and temporal resolution that provide data from similar time periods for all sites.

In this study, we chose five groups of statistical indicators to study the driving factors responsible for vegetation change. The first three groups (social, economic, and policy factors) affect ecological restoration indirectly; the fourth and fifth groups (climate and ecological factors) directly affect ecological restoration. We chose these factors based on their demonstrated importance in previous studies of our study area (Cao et al., 2009, 2017):

1 Rural social development indicators: population, agricultural labor force, and the education level of rural residents;
2 Rural economic development indicators: agricultural GDP, agricultural income, per capita income, cultivated area, aquaculture area, multiple-cropping index (i.e., the number of crops grown per year), area of terraces, total grain yield, grain yield per unit area, and livestock numbers;
3 Environmental policy indicators: area in which grazing is restricted, area in which forest harvesting is forbidden, the area of sloping land in which grazing was forbidden to allow natural recovery,

Table 3
Socioeconomic improvements from 2000 to 2016 as a result of the new project in Changting Country.

	New		Traditional		Change (%)	
	2000	2016	2000	2016	New	Traditional
Investment ($\times 10^3$ RMB km^{-2})	9.43	311.63	21.65	383.24	3204.67	1670.16
Fruit tree orchards (ha person^{-1})	0.011	0.013	0.021	0.018	17.65	−12.50
Pigs (no. person^{-1})	1.15	1.66	1.57	1.65	44.35	5.10
Fish pond area (ha person^{-1})	0.001	0.001	0.002	0.001	18.75	−20.00
Total income (RMB person^{-1})	3862	9106	6609	12318	135.78	86.38
Fruits (RMB person^{-1})	128.10	307.82	197.60	348.81	140.30	76.52
Pigs (RMB person^{-1})	268.81	1162.40	298.21	994.80	332.42	233.59
Fish (RMB person^{-1})	142.60	176.31	170.46	164.85	23.64	−3.29
Methane-generation facilities (no. per 10 000 persons)	79.31	689.81	70.99	424.32	769.76	497.72
Afforestation area (ha person^{-1})	0.17	2.43	0.36	3.71	1329.41	930.56
Area where forest harvesting is forbidden (ha person^{-1})	1.06	5.43	1.28	4.90	412.26	282.81

afforestation area, area in which artificial grassland is created, area of farmland that is replaced with natural vegetation, lengths of highways and railways that have undergone revegetation (i.e., planting of vegetation along road slopes and other excavations to create railways to conserve water and reduce erosion), the area in which revegetation of mine areas occurred, and the investment in ecological projects such as afforestation;

4 Climatic and environmental indicators: annual average temperature, annual precipitation, annual extreme temperatures, cumulative temperatures > 0 °C and > 10 °C, solar radiation, depth to groundwater, and abundance of surface water;

5 Ecological indicators: vegetation cover, species number, soil erosion, soil physical and chemical properties, and soil microorganisms.

To account for the different units of measurement for these indicators and combine them into an integrated indicator system, they must first be standardized. First, we identified the factors that changed most during our study period (1984–2016). To standardize the values of these factors, we analyzed panel data to identify the key factors using the methods of Feng et al. (2015). In summary, we performed multiple regression for the relationship between these standardized values and NDVI using the 2011 version of the STATA software (https://www.stata.com/) to identify all factors that significantly affected NDVI. We eliminated correlated variables using the Breusch-Godfrey LM test. The following variables were statistically significant ($P < 0.05$): annual mean temperature and precipitation, the rural population, the rural per capita net income, the cultivated area, the area of sloping land in which grazing was forbidden to allow natural recovery, the afforestation area, and the lengths of roads and railways and the area of mines that underwent revegetation. We used the following regression equation to describe the relationship between each selected variable and NDVI:

$$y_{it} = a + bx_{it} + u_{it} \tag{1}$$

where y_{it} represents the standardized NDVI value in year t (i.e., the % increase compared with the previous year) for area i, x_{it} is the simultaneous change in the corresponding driving factor, u_{it} is the error term, and a and b are regression coefficients.

To calculate the contributions of the significant factors identified by the regression to the NDVI changes, we used the following model:

$$Con_j = \frac{|SCV_j|}{\sum_1^j |SCV_j|} \tag{2}$$

where Con_j represents the contribution of driving factor j, and SCV_j is the standardized coefficient value for that factor (Feng et al., 2015).

To detect statistically significant differences between the test and control areas, we used least-significant difference tests. This analysis was performed using version 12.0 of the SPSS software (https://www.ibm.com/analytics).

3. Results

Because the rural population decrease had the greatest or second-greatest contribution to ecological restoration (Table 2), the county government implemented measures to assist migration from rural areas to large cities. These migrations were voluntary, but were encouraged by providing financial support, job training, and access to social benefits (e.g., school for young children). The proportion of the rural population in China is currently near 50%, which is far more than in the world's developed countries. Migration to cities appears to be an inevitable trend that is driving urbanization and accelerating socioeconomic development. Because it relieves the pressure on the land, this migration can promote ecological restoration and, if the remaining rural residents receive sufficient support, can also promote socioeconomic development. However, such large migrations will have ecological and other consequences for the urban environment. Although quantifying these consequences is beyond the scope of the present study, it will nonetheless be important to ensure that this transfer of large numbers of people from rural to urban areas does not create serious new problems.

Because much of the land in Changting County was suitable for the establishment of fruit tree orchards, the county government invested heavily in establishing these orchards. To meet rural energy needs, it was necessary to persuade residents to reduce or eliminate their use of fuel wood and take advantage of other resources; since the new government program encouraged residents to raise animals for their own use and for sale, the county government helped residents to build methane-generation facilities to use the excrement produced by this livestock as a resource. Because the ecological environment around roads and mining areas had been severely damaged by human activities, leaving these areas vulnerable to soil erosion, the county government took measures to revegetate these areas.

Table 3 compares the results of implementing the new measures with those of the traditional measures in the control villages. The number of methane-generation facilities per 10 000 people increased from 79 in 2000 to 690 in 2016 in the new project area, which was 1.5 times the rate in the control area. Similarly, the area of fruit trees increased by 17.7% in the project area, versus a decrease of 12.5% in the control area. This resulted in income increases of 140.3 and 76.5%, respectively, in the new project and control areas. The number of pigs increased by 44.4% in the new project area, versus only 5.1% in the control area. These increases led to income increases of 332.4 and 233.6%, respectively.

Table 3 also shows that the investment in the project area was always lower than that in the control area, yet greater economic and environmental returns were achieved. The new approach was also more ecologically effective. During the 16-year period after implementation of the new approach, the area with heavy soil erosion decreased by 84.4%, which is 1.7 times the rate of decrease in the control area

Table 4
The results of the new and traditional soil and water conservation approaches in the project area in Changting County from 2000 to 2016.

	New		Traditional		Change (%)	
	2000	2016	2000	2016	New	Traditional
Vegetation cover (%)	42	81.8***	73	88.4*	94.76	21.10***
Forest cover (%)	45	78.1***	71	82.6 *	73.56	16.34**
Area of soil erosion (km^2)	382	152.427**	355.7	132.74**	−60.10	−62.68
Light soil erosion (< 2500 t km^{-2} yr^{-1})	235	90.03**	244.3	70.74**	−61.69	−71.04
Moderate soil erosion (2500 to 5000 t km^{-2} yr^{-1})	45	48.89***	13.8	46.97***	8.64	240.36 **
Heavy soil erosion (5000 to 8000 t km^{-2} yr^{-1})	69	10.74**	17.7	9.15*	−84.43	−48.31***
Severe soil erosion (> 8000 t km^{-2} yr^{-1})	33	2.76***	79.9	5.88***	−91.64	−92.64
Vegetation species						
Family (no.)	4	18***	39	46*	350.00	17.95***
Genus (no.)	5	26***	57	59*	420.00	3.51***
Species (no.)	6	43***	72	75**	616.67	4.16***

Notes: Levels of significance are for the difference between 2016 and 2000, and the change (%) in project area compared with the change (%) outside of the project area: * < 0.05, ** < 0.01, *** < 0.0001.

Table 5
The contribution of each factor to the ecological restoration from 2000 to 2016 in Changting County.

		Vegetation cover		Soil erosion area		Vegetation species	
		r	Contribution (%)	*r*	Contribution (%)	*r*	Contribution (%)
Targeted measures	Rural population	−0.530**	13.78	0.195**	6.96	−0.109**	20.48
	Rural net income	0.346**	4.00	−0.746*	11.13	0.734*	8.19
	Area of fruit tree plantations	0.718**	1.81	−0.180*	3.54	0.281**	2.17
	Area in which forest harvesting is forbidden	0.209**	8.60	−0.118*	18.50	0.161**	7.61
	Methane-generation facilities	−0.759**	8.95	0.332*	3.84	−0.444**	7.45
	Length of roads and areas of mines revegetated	0.529	12.53	−0.869	16.30	0.876	13.57
	Total	–	49.67	–	60.27	–	59.47
Control area	Farmland area	0.758	13.27	−0.565	6.28	0.692*	9.84
	Afforestation area	0.432*	19.93	−0.705	24.67	0.677**	10.19
	Total	–	33.2	–	30.95	–	20.03
Climate change	Mean annual temperature	0.704	8.47	0.006	6.01	0.058	11.15
	Precipitation	0.467*	8.66	−0.640*	2.77	−0.190*	9.37
	Total	–	17.13	–	8.78	–	20.52

Notes: Significance levels: ** 1%, * 5%.

(Table 4). The vegetation cover and number of species in the new project area increased by 94.8 and 616.7%, respectively, which represent 4.5 and 148.2 times the corresponding increases in the control area. Table 5 shows the contributions of the new measures to the changes in NDVI. These measures accounted for a total of 49.7% of the vegetation cover increase, 60.3% of the soil conservation increase, and 59.5% of the species number increase.

4. Discussion

Ecological restoration aims to achieve sustainable development of both society and its economy (Tallis et al., 2008). Even when the intentions of ecological restoration are good, and the restoration strategy is suitable for the environmental conditions, it's still necessary to account for the program's socioeconomic consequences (Gong et al., 2012). Therefore, when dealing with the relationship between ecological construction and socioeconomic development, it's important to seek a balance instead of simply exploiting other resources, thereby creating different forms of environmental damage (Monbiot, 2007). Socioeconomic development and ecological restoration also affect the balance between the interests of people inside and outside the project area, and this balance plays a vital role in environmental protection (Pagiola et al., 2005; Pywell et al., 2006). Improving resident livelihoods and increasing their income can motivate them to participate in ecological restoration activities; in traditional restoration projects, people who live outside the project area often benefit from the project (e.g., by decreasing dust storms downwind of the project area), whereas residents of the project area often believe in the project's value, but because the project provides no alternative way for them to earn a living, they cannot afford to participate. Thus, the traditional approach perpetuated the "poverty trap" rather than providing an alternative (Cao et al., 2009).

The right of residents of project areas to live and earn an acceptable and sustainable living should be the highest priority (Biagini and Miller, 2013). Therefore, achieving the win–win goal of combining ecological restoration with poverty alleviation is the only path for ecological restoration that is likely to be effective in the long term in areas where residents rely on the natural resources provided by their environment for survival. Effective poverty alleviation measures help residents to adopt sustainable strategies, thereby improving the effectiveness of ecological restoration (Cao et al., 2009). When implementing an ecological restoration project, governments should therefore provide residents with stable work and income both during the project and after it ends. They can accomplish this by providing technical training, employment assistance, and funds to support the development of green industries, and by taking other measures that account for unique features of the local socioeconomic development context (Gong et al., 2012). If a project doesn't provide a good livelihood for residents, any measure that protects the environment is likely to prove useless in the long term (Enfors, 2013).

Ecosystem characteristics are complex (Byers et al., 2006), so the relationships between ecological degradation and socioeconomic development and the links between environmental protection and poverty alleviation will change over time and will differ among regions (Adams et al., 2004; Wang and Jiang, 2008). In the modern contexts of climate change, environmental degradation, and increasingly fragile

ecosystems, environmental management will require more flexible solutions than traditional measures that focused on only the ecological components of the problem (Harris, 2012). To achieve this flexibility, the present results show that it's first necessary to identify the key factors, both natural and human, that are driving ecosystem change. Managers of restoration projects can then focus on these factors, thereby providing the necessary flexibility (Zheng et al., 2015).

Degraded ecosystems are unstable in terms of landscape continuity and structure, species presence or loss, the dominant species, and interactions among trophic levels, all of which can cause changes in key aspects of the environment, such as the soils and biological community (Sasaki et al., 2008). Inappropriate ecological restoration measures will lead to further ecosystem degradation (Klotzli and Grootjans, 2001; Suding et al., 2004). Ecosystems may recover more slowly or not at all in response to natural recovery forces if they are exposed to simultaneous human interference, such as afforestation, and environmental changes, such as climate change (Liu et al., 2007). Thus, it's necessary to identify which human activities and environmental factors are interfering with natural recovery processes so that the interference can be mitigated, while also looking for ways that human activities can promote beneficial natural processes. For example, making forest management the responsibility of local residents in our study area without providing any training in sustainable forest management failed to protect the environment of our study area. In contrast, helping farmers to establish fruit tree plantations accomplished the goals that were desired for the afforestation project by planting trees, but also prevented subsequent felling of those trees by turning them into an ongoing source of income. The path to achieve ecological restoration will differ among regions because of differences in the ecosystem characteristics and climate, as well as in the socioeconomic development characteristics (Byers et al., 2006). Future ecological restoration projects must respect these differences by adopting strategies that account for these differences.

In our new approach, ecological restoration is designed to support recovery of degraded ecosystems rather than replacing them with new ones, although some new ecosystems (e.g., fruit orchards) may nonetheless be created. For example, afforestation projects often fail when they create a forest ecosystem where no forest previously existed, instead of helping the degraded ecosystem recover to its natural healthy state (e.g., grassland) (Cao et al., 2011). Our study confirmed the hypothesis that targeted measures to control ecological restoration could eliminate this blind spot in traditional thinking about ecological restoration. For example, a large rural population created additional pressure on the environment (Table 2) that could be mitigated by promoting migration to urban areas through a combination of education (to permit migrants to gain other forms of employment) and social benefits (e.g., providing access to social services). Similarly, the establishment of fruit tree orchards solved the cause of tree plantation failure by giving residents an incentive to protect the new forests (the fruit trees) in the long term by providing an ongoing source of income.

In addition, we found that the new approach decreased the cost of ecological engineering, while simultaneously producing much greater benefits. This more holistic approach to ecological restoration maximizes the long-term net benefits rather than a single indicator (such as forest cover) and short-term profits. Specifically, we identified more than key 10 factors that were responsible for vegetation cover change and ecosystem degradation in our study area; other areas will have different key driving forces that must be identified and addressed. Identifying the driving forces responsible for ecosystem evolution will require further development of the method described in the present study. In particular, it will require a focus on obtaining an increasingly full understanding of the local conditions that constrain or support ecological restoration.

Although the present study is preliminary, and must be both replicated and tested in areas with different characteristics, the problems solved by the new approach deserve attention. If the approach is suitably modified to account for local conditions, it will let policy developers in other areas design more effective restoration strategies, while also providing a theoretical basis for improved environmental protection and socioeconomic development. As this approach matures, it will provide an important solution to the poverty trap both in China, and around the world.

Author contributions

S. Cao designed the research; S. Cao, C. Xia, H. Yue, H. Ma, and G. Lin analyzed the data; and S. Cao and C. Xia wrote the paper.

Conflict of interest

The authors declare no conflicts of interest.

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